THE CONDUCTIVITY OF BRAIN TISSUES: COMPARISON OF RESULTS IN VIVO AND IN VITRO MEASUREMENTS

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Abstract-**Electric properties of tissues depend on many factors, including measurement frequency and temperature. Properties differ also in vivo and in vitro situations. We have collected conductivity values from several studies and compared the values measured from living tissue and tissue samples. The results show that the resistivity ratio of grey and white matter increases 36% after death, and the resistivity values increase over 100%.**
***Keywords* - Conductivity, brain tissue, source location**

I. INTRODUCTION

The electric properties of tissues have a very important role in biomedical engineering. These properties determine the electrical current pathways through human body. If these properties are known, electrical models can be constructed, for example, to represent the electrical activation of the heart or the conduction of the brain activity to the scalp surface.

With resistive model of the head, the information given by electroencephalography (EEG) can be effectively processed [1], [2], [3]. Models can be applied to the simulation of electric fields inside the head. For example, an electric source (dipole or set of dipoles) can be inserted inside the model and thereafter the electric field distribution can be computed. Further, the measured EEG signal can be used for obtaining the source location in the volume conductor. For example, epileptic loci can be located. In principal, accuracy of these computations is dependent on the accuracy of the volume conductor i.e. the number of compartments and their conductivities [4]. In [5] the results indicated that a 10% decrease in tissue resisitivity cause 3.0 – 4.1% differences in the sensitivity distributions of the selected 3 EEG leads. In modeling the important factor is the ratio between various conductivities. The ratio of skull and brain resistivites is 15:1 rather than the commonly used ratio of 80:1 [6]. In [7] the estimated resistivity ratio of skull and brain is 14:1.

There have been recent advances in source localization techniques. The amount of electrodes in EEG studies has been increased. Instead of the traditional 21 electrode 10–20 system, 64 or more electrodes are usually used. In some studies even 512 electrodes are utilized. This improves the spatial accuracy, thus giving more information about brain functions. However, most researchers continue to take conductivity parameters from standard references [8], [9]. The standard reference values are usually measured from tissue samples. An increase in tissue resistivity with time after death has been reported in [8], [10]. Literature values are also measured at much higher frequencies than EEG frequencies.

II. METHODOLOGY

Previously we have made in vivo resistivity measurements with needle electrode from 9 patients with brain tumors [11]. Due to the location of tumors and selected surgical paths, it was not possible to measure both grey and white matters with every patient. The number of measurements ranged from 1 to 13 for each tissue measured.

In addition to our own in vivo measurements [11], resistivity values were collected from various studies and reviews to table 1. If there were measurements made with more than one frequency, the measurements with the lowest frequency were chosen. If there were multiple measurements with same frequency, then average was taken. From [12] measurement frequency of 50 kHz was selected for comparison purposes.

Some of the tissue resistivity values were measured from animal tissues, for example from dogs, cats, or rabbits. The measurement temperatures and species for every study are shown in table 1. It is also mentioned if the measurement was done from tissue samples or from living tissues.

The frequency dependence of tissue resistivities can clearly be seen in table 1. For tissues, both relative permittivity (ε) and conductivity (σ) are strong functions of frequency. This frequency dependence (dispersion) arises from several mechanisms. For a typical soft tissue, different mechanisms dominate at different frequency ranges [13]. Electrical properties chance with frequency in three distinct steps and their dielectric constants reach enormous values at low frequencies. These steps are known as alpha (α), beta (β) and gamma (γ) dispersions [14]. The low frequency α dispersion is associated with ionic diffusion processes at the site of the cellular membrane. The β dispersion, in the hundreds of kilohertz region, is due mainly to polarization of cellular membranes, which act as barriers to the flow of ions between the intra and extra cellular media. Other contributions to the β dispersion come from the polarization of protein and other organic macromolecules. The γ dispersion, in the gigahertz region, is due to the polarization of water molecules [15]. Further information from these dispersions can be found in [9], [13], [14], and [16]. Parametric model to describe the variation of dielectric properties of tissues as a function of frequency has been developed [17].

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TABLE I
RESISTIVITY VALUES COLLECTED FROM OUR OWN MEASUREMENTS [11] AND LITERATURE

Reference	Author(s)	Grey matter (Ωm)	White matter (Ωm)	Notes
[8]	Geddes & Baker 1967	4,38 (1 kHz)	7,46 (1 kHz)	Rabbit's brain. Presumably measured from tissue samples at 39^{0}C.
[19]	Foster et al. 1979	2,67 (10 MHz)	3,33 (10 MHz)	Tissue samples from dog's brain at 37^{0}C.
[22]	Stoy et al. 1982	5,88 (100 kHz)	8,33 (100 kHz)	Tissue samples from dog's brain at 37^{0}C.
[23]	Steel & Sheppard 1985	0,50 (1,8 GHz)	0,50 (2,4 GHz)	Tissue samples from rabbit's brain at 37^{0}C.
[24]	Tay et al. 1989	4,16 (3 kHz) whole brain		Direct measurement from living cat's brain at body temperature.
[16]	Pethig 1991	2,20 (27.12 MHz)	3,00 (27.12 MHz)	Tissue samples from dog's brain at 37^{0}C.
[12]	Gabriel et al. 1996b	7,84 (50 kHz)	12,89 (50 kHz)	Tissue samples from human brain.
[20]	Bao et al. 1997	5,88 (100 kHz)	7,40 (100 kHz)	Excised rat's brain at 37^{0}C
[7]	Ferree & Tucker 1999	4,00 (1 kHz) whole brain		Human head at body temperature. Value estimated with spherical model.
[11]	Latikka et al. 2001	3,51 (50 kHz)	3,91 (50 kHz)	Direct measurement from living human brain at body temperature.

III. RESULTS

Table 1 shows the resistivity values reported in the literature. The resistivity of living tissue seems to be smaller than the resistivity of tissue sample i.e. dead tissue. This result agrees with [8] and [10].

The average of all grey matter values was 4,11and average of all white matter values was 5,85. Standard deviations were 2,37 and 3,92, respectively.

For better approximation of tissue resisitivity values in EEG frequency region, averages and standard deviations were calculated from values measured at maximum of 100 kHz. Measurements from tissue samples and from living tissue were treated separately. For dead grey matter at lower frequencies average was 5,96 and standard deviation 1,42. Dead white matter had an average of 9,02 and standard deviation of 2,61. Only one source had separated the white and grey matters when measuring the resistivity from living brain. Value for living grey matter was 3,51 and for living white matter 3,91.

The ratio of white matter resistivity / grey matter resistivity had an average of 1,51 with dead tissues. Standard deviation was 0,21. The same ratio for living tissues in [11] was 1.11. The resistivity ratio of grey and white matter changes increases 36%, and the resistance values increase over 100%.

IV. DISCUSSION

Tissue resistivity values depend on several factors. The most important factor is the frequency of the measurement current. The resistivity values decrease when measurement frequency increases. In addition tissues have three characteristic dispersion regions where resistivity decreases rapidly: alpha (α), beta (β), and gamma (γ) dispersions. These dispersion regions are due to ionic diffusion processes and polarization of several different molecules. Usually measurement frequencies are much higher than EEG frequencies, which are from 0 to 70 Hz.

Measurement of tissue resistivities at higher frequencies is also important, because frequencies between 0.1 – 100 MHz have therapeutic and diagnostic uses in medicine.

Temperature of measured tissue is also an important factor. For example, it was reported in [18] that cerebrospinal fluid has approximately 23% higher conductivity in 37 ^{0}C than in 25 ^{0}C. The grey and white matters of the brain tissue have also temperature dependence, which is shown with dog brain in [19] and with rat brain in [20].

Tissue resistivity increases after death. In [10] it was reported that there is a decrease of 62% in the current reaching the brain after death, compared with the situation in the living piglet.

In [7] the estimated resistivity ratio of skull and brain is 14:1. The same ratio calculated from the results of in vivo studies [6] and [11] is 17:1. In [5] the change in skull brain resisitivity ratio from 32:1 to 16:1 an average of 28% difference in three leads was produced. These results support the use of 15:1 skull brain resistivity ratio instead of the traditionally used ratio of 80:1 in head modeling studies.

V. CONCLUSION

Resistivity values measured from living tissues should be used in source location studies. Dead tissues have over 100% greater resistivity and the ratio of white matter and grey resistivities changes from 1,51 to 1,11 with 50 kHz measurement frequency.

Living tissue resistivity values can vary between individuals and can be affected by pathological conditions such as nearby tumors. Reference [22] indicates that possible tumors should be taken into account when source location studies are done.

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